AFOSR-TR-97

G131

REPORT DOCUMENTATION PAGE

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	Jan. 24, 1997	Final Technical, 11/15/93 to 11/14/96

4. TITLE AND SUBTITLE
Numerical Studies of Low-Density Two-Dimensional Hypersonic Flows by Using the Navier-Stokes and Burnett Equations with Nonequilibrium Real Gas Effects.

5. FUNDING NUMBERS
F-49620-94-1-0019

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
AFOSR/NA
DIRECTORATE OF AEROSPACE SCIENCES
BOLLING AFB, DC 20332-6448

NA

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
94-1-0019

11. SUPPLEMENTARY NOTES

19970314 051

12a. DISTRIBUTION/AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE
DISTRIBUTION IS UNLIMITED

13. ABSTRACT *(Maximum 200 words)*

The goal of this research is to study the laminar-turbulent transition and other transient flow phenomena of 3-D chemically-reacting hypersonic boundary layers by direct numerical simulation (DNS) and by linear stability analysis. The research in the report period was focused on developing new numerical methods for such studies and studying several fundamental transient hypersonic flow phenomena. First, several new efficient and high-order accurate numerical methods for DNS of 3-D hypersonic reacting boundary layers and for computing unsteady hypersonic flows with complex shock interactions were developed. These new methods were developed in order to overcome difficulties associated with the direct numerical simulation of hypersonic flows. Second, several studies on the stability phenomena of hypersonic boundary layers over blunt leading edges both by direct numerical simulation and by linear stability analyses were performed. Also completed were extensive numerical studies on real gas effects on a steady shock/boundary layer interaction and a self-sustained unsteady shock-shock interference heating flows. Third, the effects of using Burnett equations for rarefied hypersonic flow computations were investigated. With the completion of the bulk of work on the development of new numerical methods for complex hypersonic flow simulation, the DNS studies are currently being extended to 3-D hypersonic boundary layer transition over elliptic cross-section cones.

14. SUBJECT TERMS	15. NUMBER OF PAGES
Boundary-layer instability and transition, direct numerical simulation, hypersonic flows, shock/boundary layer interaction, real gas effects, Burnett equations, linear stability analysis	31
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

FINAL TECHNICAL REPORT

Numerical Studies of Low-Density Two-Dimensional Hypersonic Flows by Using the Navier-Stokes and Burnett Equations with Nonequilibrium Real Gas Effects

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Department of the Air Force
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Grant Number: F49620-94-1-0019
Grant Monitor: Dr. Leonidas Sakell
Final Report (15 Nov. 1993 to 14 Nov. 1996)

January 1997

Contents

1 SUMMARY

The goal of this research is to study the laminar-turbulent transition and other transient flow phenomena of 3-D chemically-reacting hypersonic boundary layers by direct numerical simulation (DNS) and by linear stability analysis. The research in the report period was focused on developing new numerical methods for such studies and studying several fundamental transient hypersonic flow phenomena. First, several new efficient and high-order accurate numerical methods for DNS of 3-D hypersonic reacting boundary layers and for computing unsteady hypersonic flows with complex shock interactions were developed. These new methods were developed in order to overcome difficulties associated with the direct numerical simulation of hypersonic flows. Second, several studies on the stability phenomena of hypersonic boundary layers over blunt leading edges both by direct numerical simulation and by linear stability analyses were performed. Also completed were extensive numerical studies on real gas effects on a steady shock/boundary layer interaction and a self-sustained unsteady shock-shock interference heating flows. Third, the effects of using Burnett equations for rarefied hypersonic flow computations were investigated. With the completion of the bulk of work on the development of new numerical methods for complex hypersonic flow simulation, the DNS studies are currently being extended to 3-D hypersonic boundary layer transition over elliptic cross-section cones.

2 OBJECTIVES

Hypersonic boundary layer laminar-turbulent transition and unsteady hypersonic aerodynamics are fundamental problems which have important practical applications in developing future maneuvering hypersonic lifting vehicles but are currently not well understood [1,2]. In recent years, DNS has become a powerful tool in the study of the stability and transition of low-speed boundary layers [3–6] and supersonic boundary layers over flat plates [7–13]. However, available DNS methods cannot be applied to hypersonic boundary layers over blunt bodies because of the effects of nose bluntness, the presence of strong shock waves, shock/boundary-layer interaction, and the real-gas effects at high temperatures.

The goal of this research is to study laminar-turbulent transition and transient flow phenomena of three-dimensional chemically-reacting hypersonic boundary layers around lifting hypersonic vehicles by direct numerical simulation and by linear stability theory (LST). The specific objectives in the report period were:

1. Develop new high-order accurate numerical methods and computer codes suitable for DNS of viscous reacting 3-D hypersonic flows over blunt bodies.
2. Study the stability and receptivity to freestream disturbances of hypersonic boundary layers over blunt bodies by DNS.
3. Study hypersonic boundary layers over blunt bodies and other wall-bounded flows by LST for comparison with DNS results.
4. Study transient hypersonic flow phenomena of reacting shock/boundary-layer interactions and shock-on-shock interference heating flows.
5. Develop a new semi-implicit algorithm for numerical simulation of unsteady viscous reacting hypersonic flows over complex maneuvering hypersonic vehicles.
6. Investigation of using the Burnett equations as the governing equations for low-density transient hypersonic flow computations.

3 ACHIEVEMENTS

Our research achievements in the report period can be classified into three areas:

1. The development of new efficient and high-order accurate numerical methods for DNS of 3-D hypersonic reacting boundary layers and for computing unsteady

hypersonic flows with complex shock interactions. The new methods include high-order semi-implicit Runge-Kutta schemes, new upwind high-order finite-difference schemes, and a simple formulation for high-order shock-fitting computations. In addition, we have applied the Essentially Non-Oscillatory [14,15] (ENO) schemes to simulate unsteady hypersonic flows with complex shock/boundary layer interaction, and have developed an efficient semi-implicit method for computing unsteady hypersonic flows over moving bodies. These new methods were developed in order to overcome the the difficulties associated with hypersonic flow simulation, i.e., the existence of strong shock waves, shock/boundary-layer interaction, and real-gas effects. The results showed that these new schemes are able to achieve efficient and high-order accuracy in the numerical simulation of transient reacting hypersonic boundary flows.

2. The investigation of several preliminary studies on the stability phenomena of hypersonic boundary layers over blunt leading edges (Fig. 1) by both DNS and LST. These simplified test cases serve as a first step in reaching our goal of DNS of 3-D boundary layer transition for lifting hypersonic vehicles. We have also completed extensive numerical studies on real gas effects on a steady shock/boundary layer interaction and a self-sustained unsteady shock-shock interference heating flows.

3. The evaluation of the Burnett solutions for rarefied hypersonic flow applications by comparing them with Navier-Stokes solutions and DSMC results for axisymmetric hypersonic flows over blunt bodies and for hypersonic Couette flow. The Burnett equations were found not to be very significant compared with the Navier-Stokes equations for steady hypersonic flows except in computing the shock-wave structure. Because of these unfavorable results and the fact that hypersonic boundary layer laminar-turbulent transition occurs mainly in the continuum regime, we have shifted the focus of our research to stability and transition of reacting hypersonic boundary layers in the continuum regime governed by the Navier-Stokes equations.

Following completion of the bulk of the work on the development of new numerical methods and computer codes for complex hypersonic flow simulations, the DNS and LST studies are being extended to 3-D hypersonic boundary layer transition over non-axisymmetric elliptic cross-section cones shown in Fig. 2 and other complex 3-D hypersonic flows.

These research accomplishments are discussed further in the following sections. More details can be found in the papers and theses listed in Section 5.

3.1 New High-Order Methods for DNS of Hypersonic Boundary Layers

Direct numerical simulation is a powerful tool for studying the fundamental flow physics of hypersonic boundary-layer transition because no empirical turbulent models are used [6]. Highly accurate and efficient numerical methods are required for such simulations in order to resolve all relevant flow time and length scales. Available DNS numerical methods for low-speed flows are inadequate for DNS of hypersonic boundary layers with strong bow shocks because of the stiffness of the reacting flow equations, the instability of high-order discretization methods for high-Mach-number flows, and the difficulty in obtaining high-order solutions containing strong shocks.

Therefore, initial research efforts were focused on developing new numerical methods that can overcome these difficulties. A new fifth (and sixth) order upwind finite difference shock fitting method has been developed for the DNS of hypersonic flows with a strong bow shock and with stiff reacting source terms. There are three main aspects of the new method: new upwind high-order finite difference schemes, a new high-order shock fitting formulation, and new third-order semi-implicit Runge-Kutta schemes. Subsequently, 3-D computer codes for these methods were developed and validated. Their numerical accuracy was tested for DNS of hypersonic flows over blunt bodies.

3.1.1 New high-order upwind schemes

Direct numerical simulation of boundary layer stability and transition requires high-order numerical methods in order to resolve a wide range of flow length scales. For hypersonic flow simulations, however, high-order finite difference schemes are often unstable when they are coupled with high-order numerical boundary conditions. In Refs. [16, 17], a new set of stable upwind fifth and seventh-order finite-difference schemes were developed for the direct numerical simulation of hypersonic boundary layers. The new schemes use central grid stencils with built-in numerical dissipation to control the numerical instability. The dissipation errors are designed to be smaller than the phase errors for well resolved length scales and to damp out unresolved shorter length scales. The numerical tests show that these upwind schemes are stable when they are coupled with high-order numerical boundary conditions, and they are more accurate than commonly used stable central schemes.

3.1.2 New high-order shock-fitting schemes

For the DNS of hypersonic boundary layers in flow over blunt bodies, the accurate computation of the unsteady curved bow shocks and their interaction with flow disturbance waves are important for the overall accuracy of the simulation. A shock-fitting approach was selected for such simulations because the unsteady bow shocks have a well-defined shape and high-order shock-fitting schemes are much more accurate than shock capturing schemes for computing hypersonic flows behind the oscillating bow shocks with disturbance/shock interaction. The use of the shock-fitting approach makes it possible to use our new fifth and sixth-order upwind schemes for flow fields behind the shocks. Therefore, a new simple formulation for high-order shock-fitting computations has been derived [16,17]. The new shock fitting formulation is much simpler than conventional shock fitting formulas for the high-order discretization of three-dimensional flow equations. Figure 3 shows a 3-D shock fitted grid for direct numerical simulations of the receptivity of hypersonic leading edges.

3.1.3 New semi-implicit Runge-Kutta schemes

The differential equations for reacting hypersonic flows are stiff for explicit numerical schemes. Implicit methods need to be used to integrate the equations efficiently. However, the accuracy of commonly used implicit methods is often only second-order, which is not accurate enough for the direct numerical simulation of boundary layer stability. In Refs. [18–20] a new set of semi-implicit Runge-Kutta schemes of up to third-order accuracy was developed for the robust and accurate temporal discretization of stiff equations for the DNS of three-dimensional reacting hypersonic flows. These new algorithms are more accurate than conventional implicit methods while maintaining the robustness for efficient calculations.

3.1.4 Computer code validation

Following the development of the new numerical methods, 3-D computer codes for the DNS of the full Navier-Stokes equations using these new methods with the option of a perfect gas model or the five-species nonequilibrium air model of Park [21] were developed. The numerical methods used in the code are the new fifth or sixth-order upwind shock-fitting finite difference schemes for spatial discretization, and third-order Runge-Kutta schemes for temporal discretization, where the new third-order semi-implicit Runge-Kutta schemes are used for real-gas simulations, and the low-storage Runge-Kutta schemes of Williamson [22] are used for perfect gas simulations.

In Ref. [17], the accuracy of the new schemes was validated on several test cases. The

code was applied to the DNS of receptivity to freestream acoustic disturbances for hypersonic boundary layer over a parabola. The results show that the new schemes are very accurate for steady and unsteady simulations of hypersonic flows with physical bow shock oscillations.

In Ref. [23], extensive testing on the robustness and accuracy of the new semi-implicit Runge-Kutta schemes for stiff equations in 1-D and 2-D reacting flow problems was performed. In Ref. [24], the new semi-implicit Runge-Kutta schemes and ENO schemes were applied to the numerical simulation of the interaction of freestream disturbances with a bow shock in reacting hypersonic flows over a blunt circular cylinder. The test results show that the new schemes are accurate and robust for reacting flow simulations.

3.2 DNS of Hypersonic Boundary Layer Stability and Transition

The receptivity mechanism provides important initial conditions of amplitude, frequency, and phase for the instability waves in the boundary layers [25–27]. For hypersonic boundary layers over blunt bodies, the receptivity phenomena are altered considerably by the presence of bow shocks over the bodies [28,29] (Fig. 1). A curved bow shock creates entropy and vorticity layers interacting with boundary layers behind it. The wave fields behind the shock are complex because of the back and forth interaction of disturbance waves between the body and the shock.

Having developed the new DNS methods and validated their associated computer codes, numerical simulations were used as a tool to study the receptivity to freestream disturbances for hypersonic boundary layers over two-dimensional blunt leading edges. The development of first- and second-mode instability waves in the boundary layers and interaction between the bow shock and freestream disturbance waves were studied by both DNS and LST approaches.

3.2.1 Boundary-layer receptivity to freestream disturbances

In Ref. [30], the DNS of the receptivity of two-dimensional hypersonic boundary layers to freestream disturbances for a two-dimensional Mach 15 flow over a parabola was performed. The full Navier-Stokes equations were solved by using the new fifth-order shock-fitting upwind scheme. The DNS results were also compared with local linear stability analysis based on mean flow solutions obtained by the numerical simulation.

The steady flow solutions for the viscous hypersonic flow over the parabola were first obtained by advancing the solutions to a steady state without freestream perturbations. Figures 4 and 5 show the steady solutions of a set of 160×120 computational grids, steady

velocity vectors, and steady entropy contours. The shock is fitted as the outer freestream boundary of the computational domain. The velocity vector plot in Fig. 5 shows the development of the boundary layer along the surface, and the entropy contours show the entropy layer developing at the edge of the boundary layer. It has been found that the accuracy of the stability analysis for hypersonic boundary layers is very sensitive to the accuracy of the mean flow solutions [31]. By using the new high-order shock-fitting scheme, we are able to obtain high-accuracy "clean" mean flow solutions for the unsteady calculations as well as for the LST analyses for hypersonic boundary layers over blunt bodies.

The unsteady simulation was performed by imposing freestream disturbances to the freestream. The results showed that the instability waves developed in the hypersonic boundary layer behind the bow shock contain both the first and second mode instabilities. The results also indicated that external disturbances, especially the entropy and vorticity ones, enter the boundary layer to generate instability waves mainly in the leading edge region. Figure 6 shows the contours for the instantaneous perturbation of the vertical velocity components after the flow field reached a periodic state. The disturbance field is a combination of the external forcing disturbance waves and the T-S waves in the boundary layer. The contours show the development of the Tollmien-Schlichting (T-S) waves in the boundary layer on the parabola surface. From the instantaneous contours in Fig. 6, it is clear that the instability waves developed in the wall have two separate zones. The first zone is located in the region of $x < 0.2$ and the second one is located in the region of $x > 0.2$. It was shown that the instability wave developed in the first region is the first mode instability and that the wave in the second region is the second mode instability. Figure 7 shows the contours for the instantaneous perturbation of velocity vectors. The oscillations of the bow shock were resolved by the simulation and can be seen in this figure.

Further parametric studies on the first and second instability mode developments and the effects of bow shock interaction are currently under way.

3.2.2 Bow-shock/freestream disturbance interactions

The interaction between the bow shock and disturbance waves from the freestream is a major uncertainty in the studies of the transition of hypersonic boundary layers. Detailed numerical and analytical studies on the inviscid wave fields generated by the interaction between the bow shock and freestream disturbances in hypersonic flows over cylinders have been performed.

In Refs. [32, 33], the effects of the bow shock on ideal inviscid flow interacting with freestream disturbance waves for Mach 8 flow over a circular cylinder have been investigated using both linear analysis and numerical simulation. It was shown that due to the nonuni-

formity of the background mean flow fields, there is a singularity of the inviscid entropy and vorticity waves on the body surface in the solutions of the Euler equations. This singularity creates a range of new length scales for entropy and vorticity waves approaching the solid surface. It was also shown that wave perturbations generated behind the shock are considerably amplified by wave interaction between the bow shock and the body.

In Ref. [24], the nonequilibrium real gas effects on the bow-shock/freestream acoustic wave interaction in hypersonic flow over a cylinder were studied by numerical simulation and by approximate linear analysis. The governing equations are the Euler equations with finite-rate chemical reactions and vibrational relaxation. It was shown that real gas effects reduce the intensity of the singularity of entropy and vorticity waves near the wall and smear out small wave length scales.

These results may be important for hypersonic boundary-layer receptivity phenomena because it is these shorter waves that enter the hypersonic boundary layers and induce instability waves and transition.

3.3 Linear Stability Analysis of Hypersonic Flows

Much of our knowledge on the stability properties of supersonic and hypersonic boundary layers is based on the LST work of Mack [34,35]. For hypersonic flow over blunt bodies, the stability characteristics of hypersonic boundary layers over a blunt cone corresponding to Stetson's experiments [36] have been studied using LST [31,37–39]. Though some observations on the effects of bluntness and the entropy layer are consistent with linear stability analysis, the second-mode instability and the general amplification characteristics in the blunt cone flows do not agree with the experiments. The reason for the discrepancy is currently not clear. Possible reasons include the fact that the LST for hypersonic flow over a blunt cone has the difficulty of obtaining highly-accurate steady base flow for the stability equations. In addition, the effects of the bow shock and non-parallel boundary layers on the disturbance fields may not be adequately considered in the LST. Because DNS can provide the detailed solutions of the unsteady flow fields, the discrepancy between the LST and experiments may be resolved by comparing with DNS results. Therefore, LST analysis of the stability of hypersonic boundary layers over blunt bodies was conducted for comparison with the DNS results.

As a first step, we [40] developed two compressible global linear stability codes and have studied the linear stability of hypersonic Couette flows which are currently not well understood. High-Mach-number instability modes had not previously been found for compressible Couette flow at finite Reynolds numbers [41]. In Ref. [40], unstable second modes were found for Mach 5 and 10 flow with critical Reynolds numbers to be around 9×10^4 and 2.6×10^5

respectively. The neutral stability curves for those Mach numbers are shown in Fig. 8. The effects of Mach numbers, three dimensionality, and the wall cooling on the stability of hypersonic Couette flow were also studied.

Subsequently, linear stability analysis on hypersonic flow over blunt leading edges was conducted [30] for comparison with the DNS results. The LST results compare reasonably well with DNS results for frequency, but the agreement is not as good for the growth rates. These results are consistent with the comparisons between LST and experimental results for hypersonic boundary layers over axisymmetric cones. We are currently modifying the LST equations and investigating the cause of the discrepancy. The next step is to extend the theoretical studies to solving PSE for hypersonic boundary layer stability simulation.

3.4 Hypersonic Shock/Boundary-Layer Interactions with Real Gas Effects

3.4.1 Unsteady shock/boundary-layer interactions

Shock-wave/boundary-layer interaction and shock-shock interference heating phenomena occur in many external and internal hypersonic flow fields. These interactions introduce severe local surface heatings, and they can induce boundary layer separations and laminar-turbulent transition. For high-enthalpy hypersonic flows, real gas effects are expected to have a strong impact on flow structure and heating rates. Previous studies of such interactions have been mainly limited to ideal gas flows [42] or real-gas interactions of steady flows only [43–47].

In Ref. [48], numerical simulation of the shock/boundary layer interaction and the unsteady hypersonic shock-shock interference heating flows using the perfect gas assumption were performed. It was shown that certain shock-shock interference heating flow fields are inherently unstable. This instability has strong effects on the aerodynamic heating to a solid surface. In [49–53], extensive numerical studies on real gas effects on a steady shock/boundary layer interaction and a self-sustained unsteady shock-shock interference heating flow were performed. It was shown that real gas effects reduce surface heating and pressure, and the shock-shock interference flow with chemical reactions are inherently unsteady with strong vortex shedding from the interaction points.

Figure 9 shows a schematic of the type IV shock interference heating problem, which is characterized by an oblique shock impinging on a bow shock in front of a blunt body. A type IV interference heating flow over a cylinder with a pure N_2 freestream at Mach 8.03 are studied by numerical simulations. Figure 10 shows the instantaneous dissociated N mass fraction contours. The self-sustained oscillation of the supersonic jet can be seen by

tracing the mass fraction contours along their time history. The numerical simulations show that the type IV shock-shock interference flow field with nonequilibrium real gas effects is inherently unsteady. The unsteady mechanism is related to the shedding of vortices from the jet impingement region near the surface of the cylinder.

3.4.2 ENO schemes for transient hypersonic flow simulation

For hypersonic flows with complex shock interactions, the high-order shock-fitting methods cannot be used because of the difficulties of fitting complex shock interactions. High-order Essentially Non-Oscillatory (ENO) schemes [14,15] offer the best accuracy in computing transient shock interaction by capturing the shock waves as a part of the numerical solutions. The main advantage of the ENO schemes is their ability in capturing complex shock interaction with uniformly high-order accuracy. Though less accurate than the high-order shock-fitting schemes, the ENO shock capturing schemes are able to simulate transient flow fields with complex shock/boundary interactions. Therefore, in addition to using our high-order shock-fitting schemes, the ENO schemes were used for the DNS of reacting hypersonic boundary layers with complex shock/shock or shock/boundary-layer interactions.

In Refs. [32,48], the high-order ENO schemes for capturing shock waves were applied to the computation of nonequilibrium viscous hypersonic flows. Extensive validating calculations were conducted on the ENO schemes for viscous hypersonic flow applications. It was shown that the ENO schemes are adequate for computing transient hypersonic flows with complex shock waves. In addition, a M.S. student is currently working on the development of parallelization of hypersonic reacting flow computations on IBM SP-2 computers for the 3-D direct simulations of stability and transitions of hypersonic boundary layers.

3.5 Unsteady Viscous Hypersonic Flow Simulation

One of the difficulties for the time-accurate computations of unsteady viscous hypersonic flows around 3-D maneuvering vehicles is that the thin viscous layers on the body surface require implicit treatment. Current global implicit methods are computationally expensive for time-accurate 3-D unsteady viscous reactive flow computations.

The idea of high-order semi-implicit Runge-Kutta schemes [18,19] was used to develop accurate numerical methods for computing unsteady nonequilibrium hypersonic flow around maneuvering vehicles. In Ref. [54], a semi-implicit method was presented for efficient and high-order accurate computations of unsteady viscous hypersonic flows over fixed or moving bodies. The semi-implicit method was used to remove the stiffness caused by the small grid

sizes along the wall-normal direction in the boundary layers. The spatial discretization of the governing equations was separated into stiff terms involving derivatives along the wall-normal direction and non-stiff terms of the rest of the equations. The split equations were then advanced in time using the third-order semi-implicit Runge-Kutta schemes, which led to efficient computations of block pentadiagonal diagonal systems of implicit equations. The performance of the new semi-implicit scheme for the Navier-Stokes equations was tested in unsteady hypersonic flow over an oscillating blunt leading edge. The numerical tests show that the semi-implicit method is efficient for solving the Navier Stokes equations in highly stretched grids across boundary layers.

The new method will be extended to the DNS of hypersonic boundary layers to increase the computational efficiency of explicit computations in thin boundary layers.

3.6 Burnett Equations

The Burnett equations are a higher-order approximation to the Boltzmann equation than the Navier-Stokes equations for rarefied gas flows. We had developed numerical methods for simulation of hypersonic flows using the Burnett equations and evaluated their usefulness for potential applications to hypersonic flows in the rarefied gas flow regime.

In Ref. [55], the general 3-D components of the Burnett stress and heat-flux terms were derived from the general tensor forms and extended our numerical method for solving the planar 2-D augmented Burnett equations to axisymmetric ones. The Burnett solutions were compared with Navier-Stokes solutions and DSMC results. In Ref. [56], the Burnett solutions for Couette flow at various Mach numbers and Knudsen numbers were evaluated by comparing them with the DSMC results. The results showed that when the Burnett equations are valid, the Burnett solutions are not very different from the Navier-Stokes results. The only exception is that the Burnett solutions predict a much thicker shock wave than the Navier-Stokes equations in the temperature profiles across the shock waves, which may be significant for some applications.

However, our attempt in obtaining numerical Burnett solutions for 2-D hypersonic flow over a sharp leading edge was not successful due to the severe nonequilibrium effect near the leading edge. It is also reported that Forrest Lumpkin at NASA Ames could not obtain solutions of the augmented Burnett equations for expanding flow in the highly rarefied base region of a cylinder [57]. These difficulties together with the analytical analysis on the entropy properties of the Burnett equations by Comeaux et al. [57] at Stanford University suggest that the Burnett equations may not be appropriate for hypersonic flow that is very far from the continuum regime. In other word, for hypersonic flow with large local Knudsen numbers, especially in the expansion flow, the computations of the Burnett equations will fail to obtain

solutions. Thus, the applications of Burnett equations to steady nonequilibrium hypersonic flow probably may not be very significant for many situations, and may not work for flow with very high local Knudsen numbers.

Overall, the Burnett equations may not be significant for steady hypersonic flows at very high nonequilibrium conditions except for computing the shock structure. Therefore, we have shifted the focus of our investigation to the stability equations for hypersonic flows using the Navier-Stokes equations, because the stability and transition of hypersonic boundary layers occurs at higher Reynolds number in the continuum regime.

4 PERSONNEL

The following personnel conducted research for the grant and were partially supported by the grant:

1. Xiaolin Zhong, principal investigator.
2. Gregory H. Furumoto, passed Ph.D. thesis defense in December 1996, and will receive his Ph.D. degree in March 1997.
3. John C. Skiba, received M.S. degree in Aerospace Engineering at UCLA in June 1994. He is currently an engineering specialist at Hughes Missile System Co., Tucson, Arizona.
4. Chien-Erh Chiu, received his M.S. degree in Mechanical Engineering at UCLA in June 1994, and returned to Taiwan after graduation.
5. Xavier Joubert, was partially supported as a visiting student from France. He returned to France in September 1995.
6. Dr. J. W. Shen, was partially supported as a research associate from December 1996 to December 1997.
7. Sean H. Hu, a Ph.D. student.
8. Jack J. Yoh, a Ph.D. student.
9. Haibo Dong, a Ph.D. student.
10. Theodore K. Lee, a M.S./Ph.D. student.

5 PUBLICATIONS

The following publications were completed from work supported by this grant:

In Journals or Books:

1. X. Zhong, "Application of Essentially Nonoscillatory Schemes to Unsteady Hypersonic Shock-Shock Interference Heating Problems", *AIAA Journal*, Vol. 32, No. 8, pp. 1606-1616, 1994.

2. X. Zhong and G. H. Furumoto, "Augmented Burnett Equation Solutions over Axisymmetric Blunt Bodies in Hypersonic Flow," *Journal of Spacecraft and Rockets*, Vol. 32, No. 4, pp. 588-595, 1995.

3. X. Zhong and K. Koura, "Comparison of Solutions of the Burnett Equations, Navier-Stokes Equations, and DSMC for Couette Flow," In *Rarefied Gas Dynamics*, Vol. I, edited by J. Harvey and G. Lord, Oxford University Press, Oxford, pp 354-360, 1995.

4. C.-E. Chiu and X. Zhong, "Numerical Simulation of Transient Hypersonic Flow Using the Essentially Nonoscillatory Schemes," *AIAA Journal*, Vol. 34, No. 4, pp. 655-661, 1996.

5. X. Zhong, "Additive Semi-Implicit Runge-Kutta Methods for Computing High-Speed Nonequilibrium Reactive Flows," *Journal of Computational Physics*, Vol. 128, pp. 19-31, 1996.

6. G. H. Furumoto, X. Zhong, and J. C. Skiba, "Numerical Studies of Real-Gas Effects on Two-Dimensional Hypersonic Shock-Wave/Boundary-Layer Interaction," *Physics of Fluids*, Vol. 9, No. 1, pp. 191-210, January 1997.

In Conference Proceedings:

1. X. Zhong and G. H. Furumoto, "Solutions of the Burnett Equations for Axisymmetric Hypersonic Flow Past Spherical Blunt Bodies," AIAA paper 94-1959, July 1994.

2. C.-E. Chiu and X. Zhong, "Simulation of Transient Hypersonic Flow Using the ENO Schemes," AIAA paper 95-0469, Jan. 1995.

3. X. Zhong, "New High-Order Semi-Implicit Runge-Kutta Schemes for Computing Transient Nonequilibrium Hypersonic Flow," AIAA Paper 95-2007, June 1995.

4. X. Zhong, X. Joubert, and T. K. Lee, "Bow-Shock/Disturbance Interaction for Hypersonic Flow over a Cylinder," 20th International Symp. on Shock Waves, Pasadena, California, July 1995.

5. G. H. Furumoto, X. Zhong, and J. C. Skiba, "Unsteady Shock-Wave Reflection and Interaction in Viscous Flow with Thermal and Chemical Nonequilibrium," AIAA Paper 96-0107, Jan. 1996.

6. X. Zhong, "High-Order Finite-Difference Shock-Fitting Schemes for Direct Numerical Simulation of Hypersonic Boundary-Layer Receptivity to Free-Stream Disturbances," First AFOSR Conference on Dynamic Motion CFD, New Brunswick, New Jersey, June 1996.

7. G. H. Furumoto and X. Zhong, "Unsteady Shock-Shock Interference Heating with Nonequilibrium Real Gas Effects," First AFOSR Conference on Dynamic Motion CFD, New Brunswick, New Jersey, June 1996.

8. J. W. Shen and X. Zhong, "Semi-Implicit Runge-Kutta Schemes for Non-Autonomous Differential Equations in Reactive Flow Computations," AIAA paper 96-1969, June 1996.

9. X. Zhong and T. K. Lee, "Nonequilibrium Real-Gas Effects on Bow-Shock/Disturbance Interaction in Hypersonic Flow Past a Cylinder," AIAA paper 96-1856, June 1996. June, 1996.

10. S. H. Hu and X. Zhong, "Linear Instability of Compressible Plane Couette Flow," AIAA paper 97-0432, Jan. 1997.

11. G. H. Furumoto and X. Zhong "Numerical Simulation of Viscous Unsteady Type IV Shock-Shock Interaction with Thermochemical Nonequilibrium," AIAA paper 97-0982, Jan. 1997.

12. X. Zhong, "Direct Numerical Simulation of Hypersonic Boundary-Layer Transition Over Blunt Leading Edges, Part I: New Numerical Method and Validation," AIAA paper 97-0755, Jan. 1997.

13. X. Zhong, "Direct Numerical Simulation of Hypersonic Boundary-Layer Transition Over Blunt Leading Edges, Part II: Receptivity to Sound," AIAA paper 97-0756, Jan. 1997.

14. X. Zhong and J. W. Shen, "An Efficient Semi-Implicit Time-Accurate Scheme for Unsteady Viscous Flow on Dynamic Grids," AIAA paper 97-0726, Jan. 1997.

15. J.J. Yoh and X. Zhong, "Semi-Implicit Runge-Kutta Schemes for Stiff Multi-Dimensional Detonation Flows," AIAA paper 97-0803, Jan. 1997.

16. S. Hu and X. Zhong, "Linear Stability Analysis and PSE Simulation of Reacting Hypersonic Wall-Bounded Shear Flows," Accepted by the 20th AIAA Fluid Dynamics Conference, Snowmass, Colorado, June 1997.

Ph.D. or M.S. Theses:

1. Gregory Furumoto, "Unsteady Shock-Wave Reflection and Interaction in Viscous Flow with Thermal and Chemical Nonequilibrium," Passed Thesis Exam for Ph.D. in Mechanical and Aerospace Engineering, UCLA, Dec. 1996.

2. John Skiba, "Hypersonic Oblique Shock-Wave/Laminar Boundary-Layer Interaction in Thermal and Chemical Nonequilibrium," M.S. in Aerospace Engineering, UCLA, June 1994.

3. Chien-Erh Chiu, "Simulation of transient hypersonic flows using the Essentially Non-Oscillatory schemes," M.S. in Mechanical Engineering, UCLA, June 1994.

6 TECHNICAL PRESENTATIONS

1. X. Zhong and G. H. Furumoto, "Solutions of the Burnett Equations for Axisymmetric Hypersonic Flow Past Spherical Blunt Bodies," AIAA/ASME 6th Joint Thermophysics and Heat Transfer Conf., Colorado Spring, CO, June 1994.

2. X. Zhong and K. Koura, "Comparison of Solutions of the Burnett Equations, Navier-Stokes Equations, and DSMC for Couette Flow," 19th International Symposium on Rarefied Gas Dynamics Oxford, July 1994.

3. X. Zhong, "Numerical Simulation of Transient Hypersonic Flow," (invited seminar), UCLA-Caltech Applied Math Seminars, Nov., 1994.

4. X. Zhong, and C.-E. Chiu "Transient Hypersonic Shock-Shock Interference Heating on a Cylinder," APS Division of Fluid Dynamics Meeting, Nov. 1994.

5. C.-E. Chiu and X. Zhong, "Simulation of Transient Hypersonic Flow Using the ENO Schemes," AIAA 33rd Aerospace Science Meeting, Reno, NV, Jan. 1995.

6. X. Zhong, "Numerical Simulations of Hypersonic Flows," (invited seminar), Japan National Aerospace Lab, Tokyo, Japan, March 1995.

7. X. Zhong, "New High-Order Semi-Implicit Runge-Kutta Schemes for Computing Transient Nonequilibrium Hypersonic Flow," AIAA Thermophysics Conference, San Diego, CA, June 1995.

8. X. Zhong, X. Joubert, and T. K. Lee, "Bow-Shock/Disturbance Interaction for Hypersonic Flow over a Cylinder," 20th International Symp. on Shock Waves, Pasadena, California, July 1995.

9. X. Zhong, "Bow-Shock/Disturbance Interaction in Hypersonic Flow Over a Cylinder with Nonequilibrium Real Gas Effects," American Physical Society (APS) Division of Fluid Dynamics Meeting, Irvine, CA, Nov. 1995.

10. G. H. Furumoto, X. Zhong, and J.C. Skiba, "Unsteady Hypersonic Shock-Wave/Boundary Layer Interaction with Nonequilibrium Real Gas Effects," APS Division of Fluid Dynamics Meeting, Irvine, CA, Nov. 1995.

11. X. Joubert and X. Zhong, "Direct Numerical Simulations of Receptivity of Hypersonic Boundary Layer on a Blunt Leading Edge," APS Division of Fluid Dynamics Meeting, Irvine, CA, Nov. 1995.

12. G. H. Furumoto, X. Zhong, and J. C. Skiba, "Unsteady Shock-Wave Reflection and Interaction in Viscous Flow with Thermal and Chemical Nonequilibrium," AIAA 34th Aerospace Sciences Meeting and Exhibit, Reno, NV, Jan. 1996.

13. X. Zhong, "Transient Shock/Boundary-Layer and Shock/Disturbance Interaction in Hypersonic Flows Over Blunt Bodies," (invited seminar), Graduate Aeronautical Laboratories, California Institute of Technology, Jan. 1996.

14. X. Zhong, "Transient Shock/Boundary-Layer and Shock/Free-Stream Disturbance Interaction in Hypersonic Flows Over Blunt Bodies," (invited seminar), Aerospace Engineering Department, Purdue University, June 1996.

15. X. Zhong, "High-Order Finite-Difference Shock-Fitting Schemes for Direct Numerical Simulation of Hypersonic Boundary-Layer Receptivity to Free-Stream Disturbances," First AFOSR Conference on Dynamic Motion CFD, New Brunswick, New Jersey, June 1996.

16. G. H. Furumoto and X. Zhong, "Unsteady Shock-Shock Interference Heating with Nonequilibrium Real Gas Effects," First AFOSR Conference on Dynamic Motion CFD, New Brunswick, New Jersey, June 1996.

17. J. W. Shen and X. Zhong, "Semi-Implicit Runge-Kutta Schemes for Non-Autonomous Differential Equations in Reactive Flow Computations," AIAA 27th Fluid Dynamics Conference, New Orleans, LA, June 1996.

18. X. Zhong and T. K. Lee, "Nonequilibrium Real-Gas Effects on Bow-Shock/Disturbance Interaction in Hypersonic Flow Past a Cylinder," AIAA 31st Thermophysics Conference, New Orleans, LA, June 1996.

19. S. H. Hu and X. Zhong, "Linear Instability of Supersonic Plane Couette Flow," 1996 Division of Fluid Dynamics meeting of the APS, Nov. 1996.

20. M. Tatineni and X. Zhong, "Numerical Simulation of Unsteady Low-Reynolds-Number Separated Flows Over Airfoils," 1996 Division of Fluid Dynamics meeting of the APS, Nov. 1996.

21. X. Zhong, "Direct Numerical Simulation of the Instability of Hypersonic Shear and Boundary Layers," 1996 Division of Fluid Dynamics meeting of the APS, Nov. 1996.

22. J. J. Yoh and X. Zhong, "Numerical Simulation of Multi-Dimensional Detonation Using Semi-Implicit Runge-Kutta Schemes," 1996 Division of Fluid Dynamics meeting of the APS, Nov. 1996.

23. S. H. Hu and X. Zhong, "Linear Instability of Compressible Plane Couette Flow," 35th AIAA Aerospace Science Meeting and Exhibit, Reno, NV, Jan. 1997.

24. G. H. Furumoto and X. Zhong "Numerical Simulation of Viscous Unsteady Type IV Shock-Shock Interaction with Thermochemical Nonequilibrium," 35th AIAA Aerospace Science Meeting and Exhibit, Reno, NV, Jan. 1997.

25. X. Zhong, "Direct Numerical Simulation of Hypersonic Boundary-Layer Transition Over Blunt Leading Edges, Part I: New Numerical Method and Validation," (invited paper), 35th AIAA Aerospace Science Meeting and Exhibit, Reno, NV, Jan. 1997.

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27. X. Zhong and J. W. Shen, "An Efficient Semi-Implicit Time-Accurate Scheme for Unsteady Viscous Flow on Dynamic Grids," 35th AIAA Aerospace Science Meeting and Exhibit, Reno, NV, Jan. 1997.

28. J.J. Yoh and X. Zhong, "Semi-Implicit Runge-Kutta Schemes for Stiff Multi-Dimensional Detonation Flows," 35th AIAA Aerospace Science Meeting and Exhibit, Reno, NV, Jan. 1997.

7 ACKNOWLEDGMENTS

In addition to the main AFOSR grant F49620-94-1-0019, this research was also supported by AFOSR AASERT grant F49620-94-1-0019. Both grants are monitored by Dr. Len Sakell.

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9 FIGURES

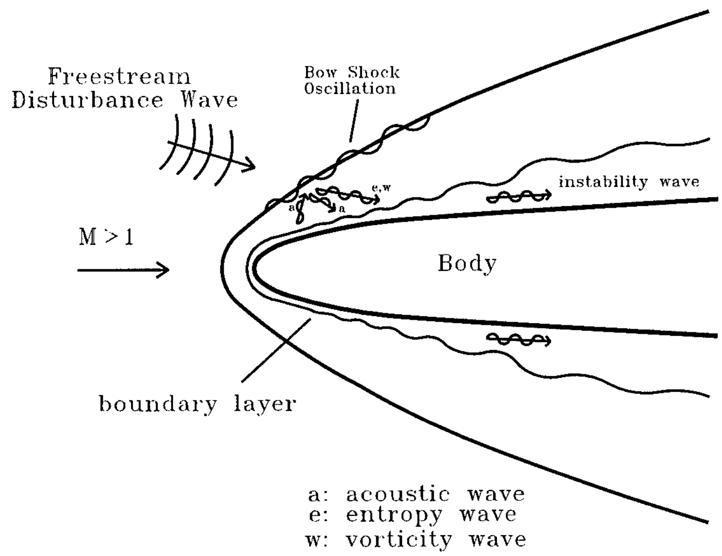


Figure 1: The interaction between the bow shock and disturbance fields. The disturbances can originate either from the freestream, surface roughness, or surface vibrations.

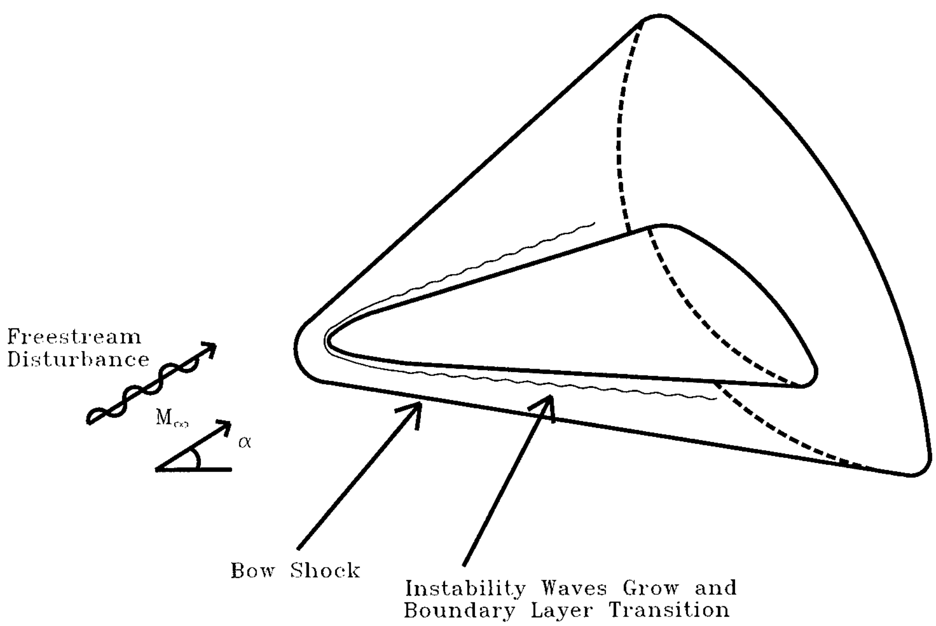


Figure 2: The hypersonic flow field in the direct numerical simulation of 3-D reacting hypersonic boundary-layer receptivity to freestream disturbances over a blunt elliptic cross-section cone.

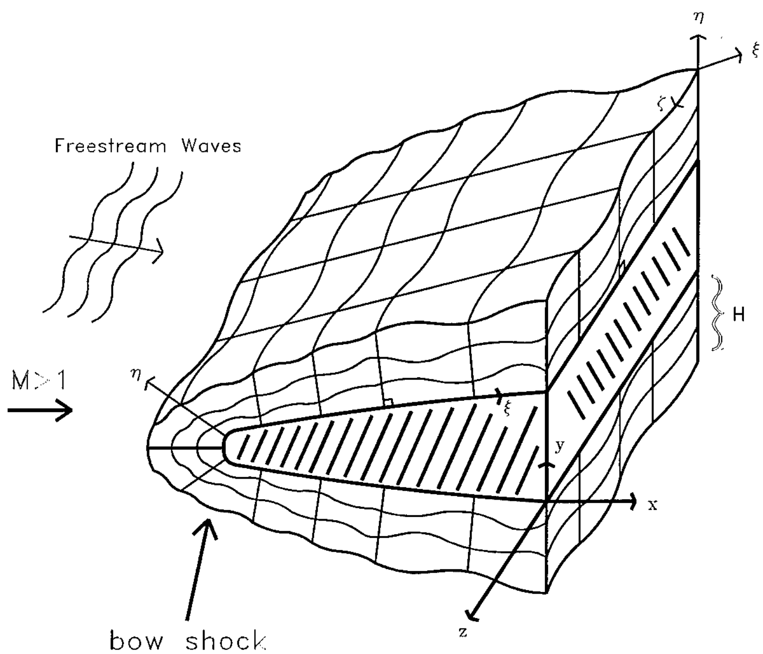


Figure 3: A schematic of 3-D shock fitted grids for the direct numerical simulation of hypersonic boundary-layer receptivity to freestream disturbances over a blunt leading edge.

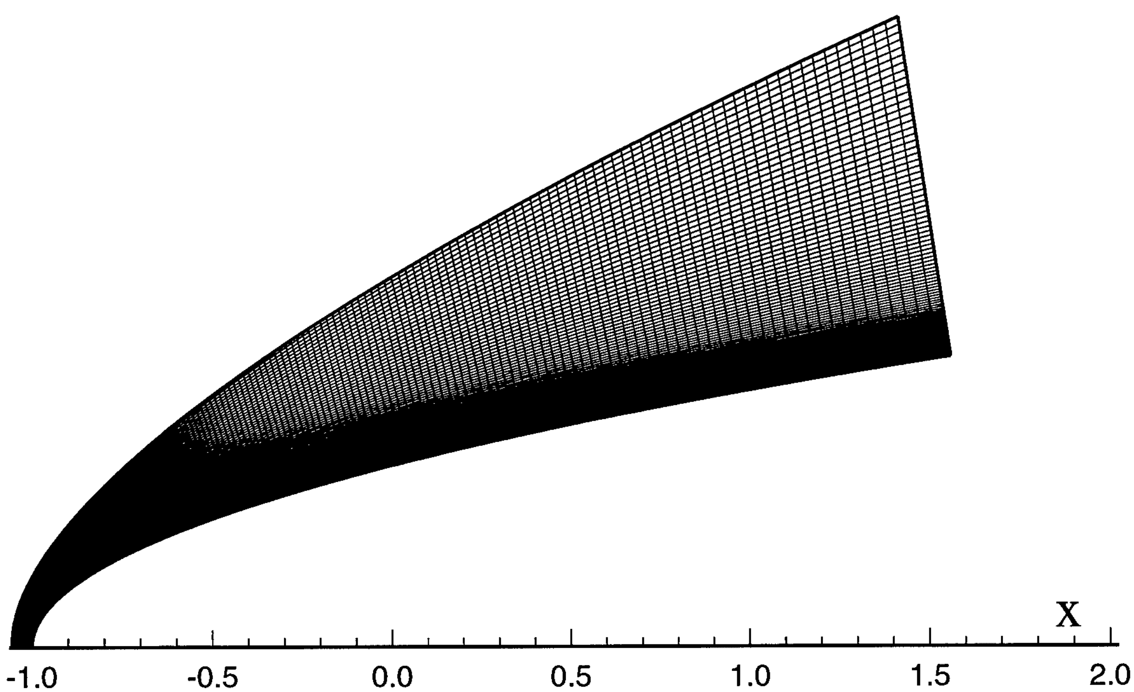
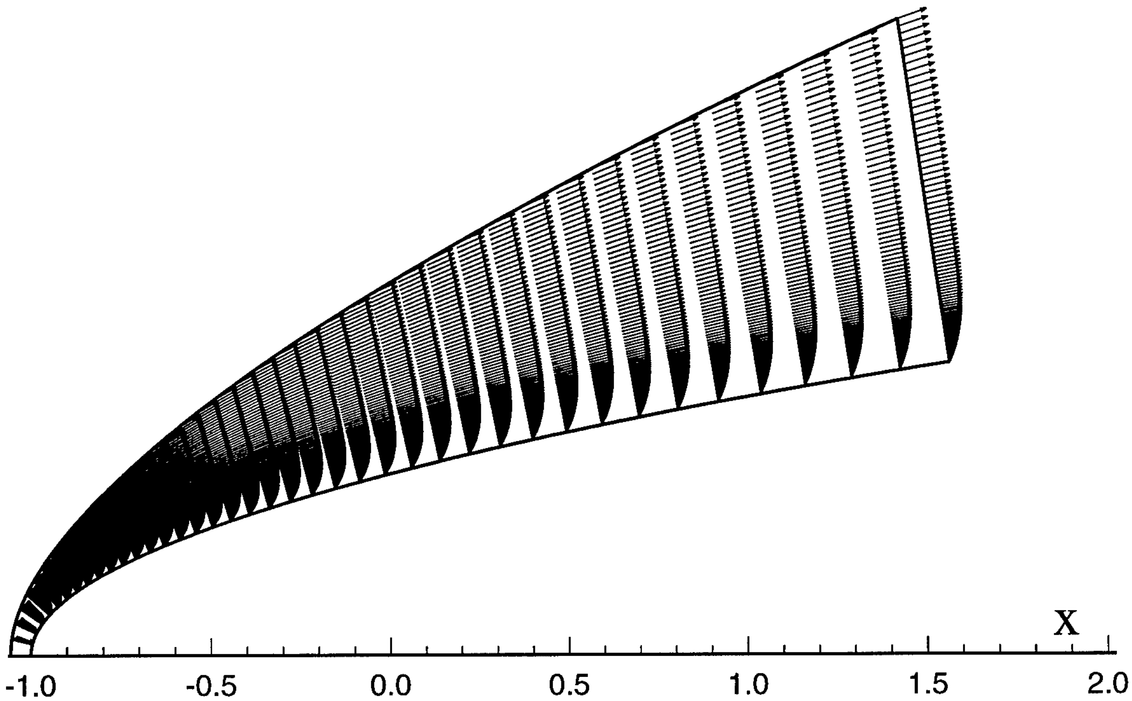


Figure 4: Computational grid for the DNS of the receptivity to a weak freestream monochromatic planar acoustic waves by a hypersonic boundary layer over a parabola. The bow shock shape is obtained as the numerical solution for the freestream grid line. ($M_\infty = 15$ and $Re_\infty = \rho^*_\infty U^*_\infty d^* / \mu^*_\infty = 6026.55$)



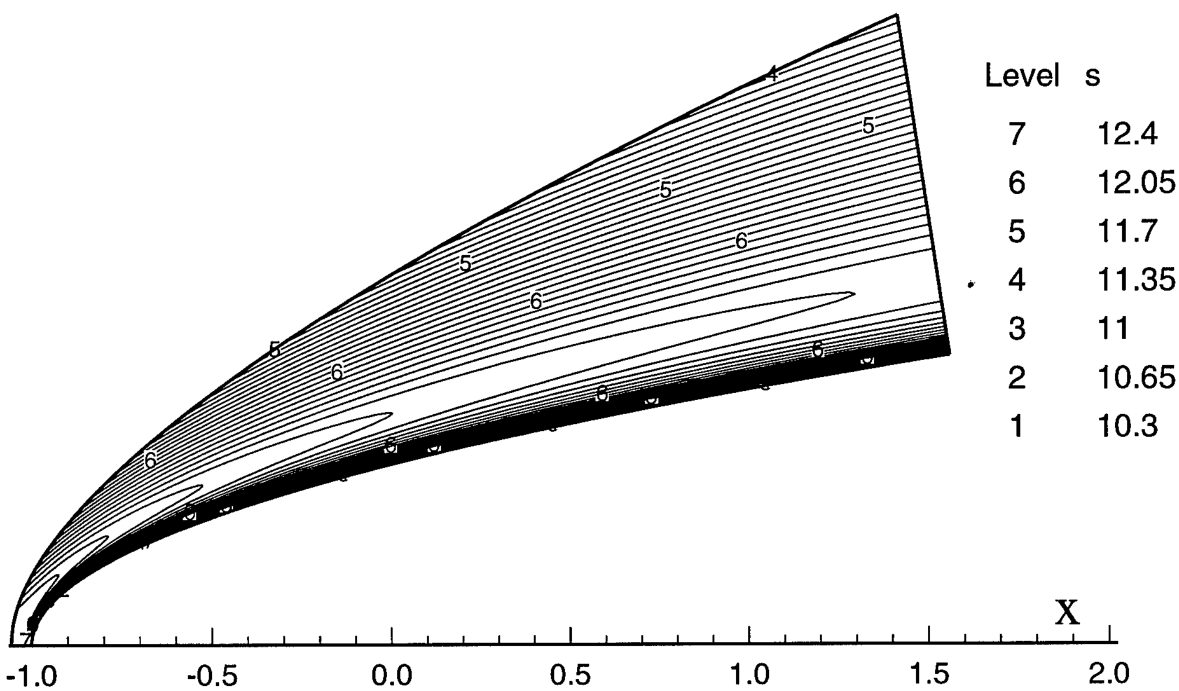


Figure 5: Steady base flow solutions of velocity vectors and entropy contours for the DNS of the receptivity to a weak freestream acoustic waves by a hypersonic boundary layer over a parabola ($M_\infty = 15$ and $Re_\infty = 6026.55$).

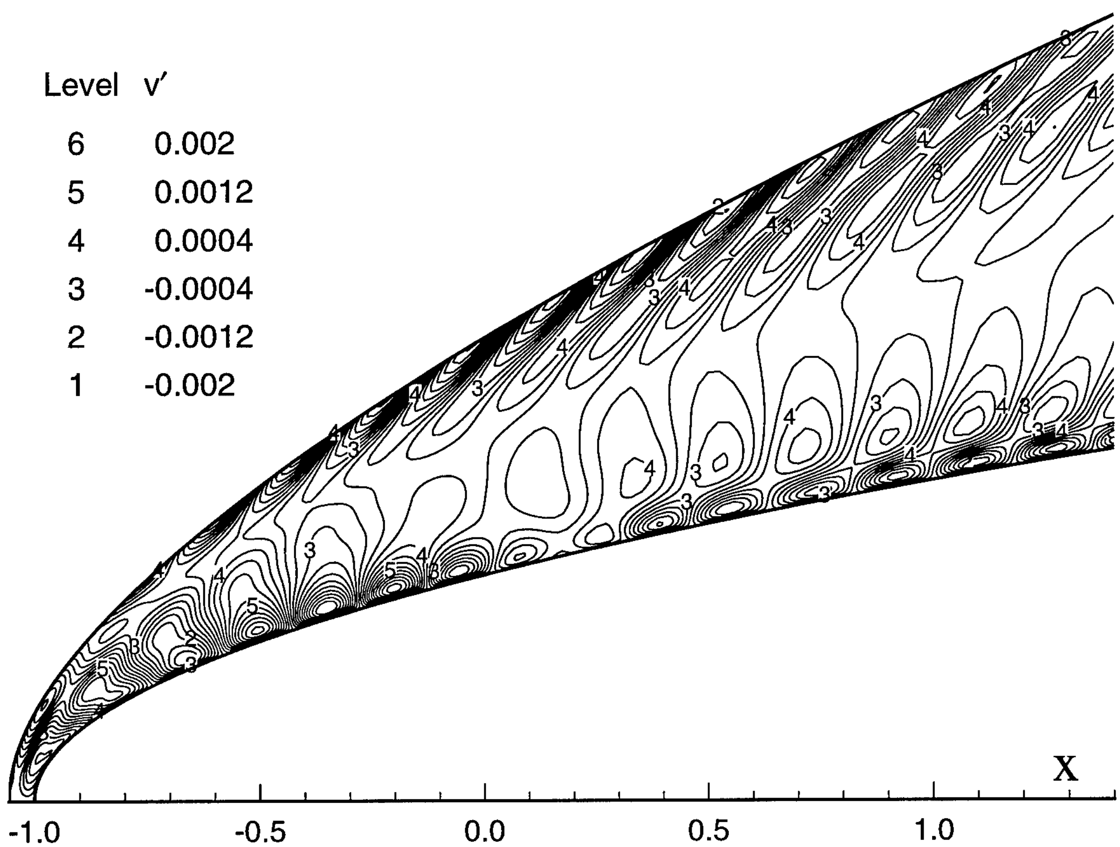


Figure 6: Instantaneous vertical velocity perturbation contours for the DNS of the receptivity to a weak freestream acoustic waves by a hypersonic boundary layer over a parabola ($M_\infty = 15$ and $Re_\infty = 6026.55$).

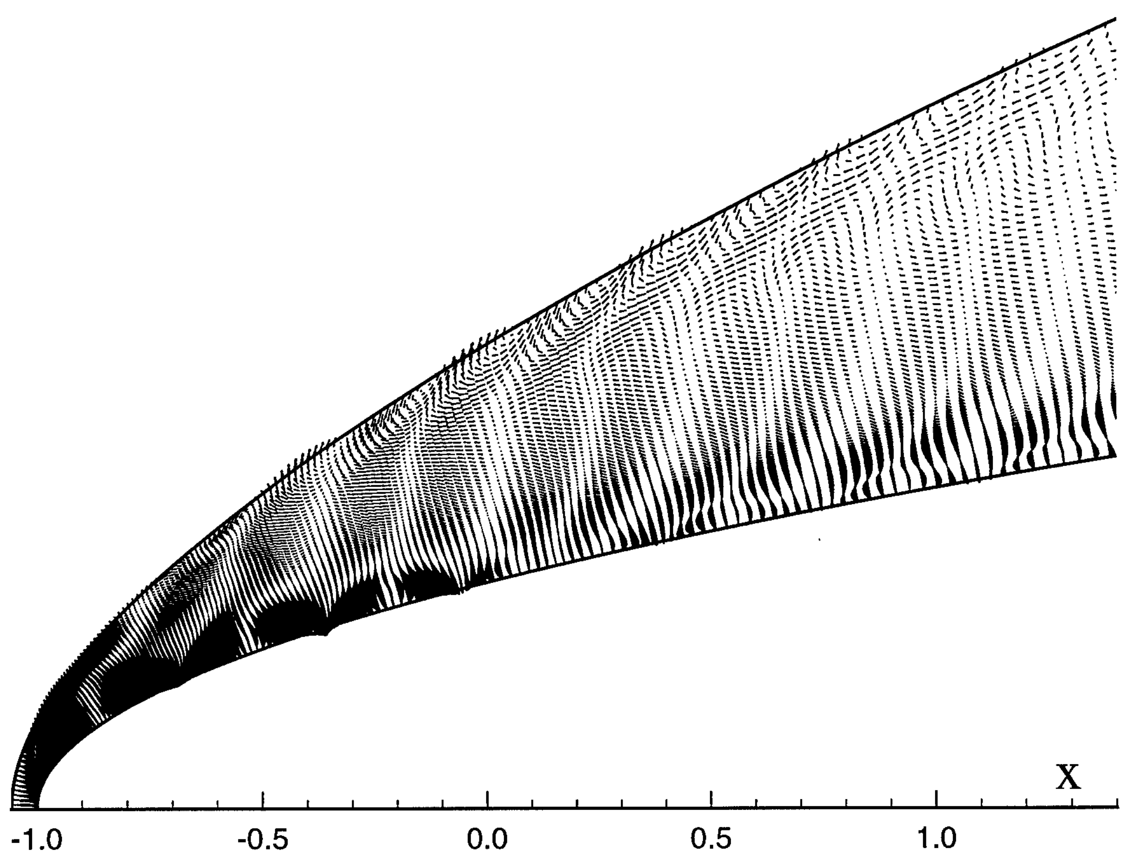
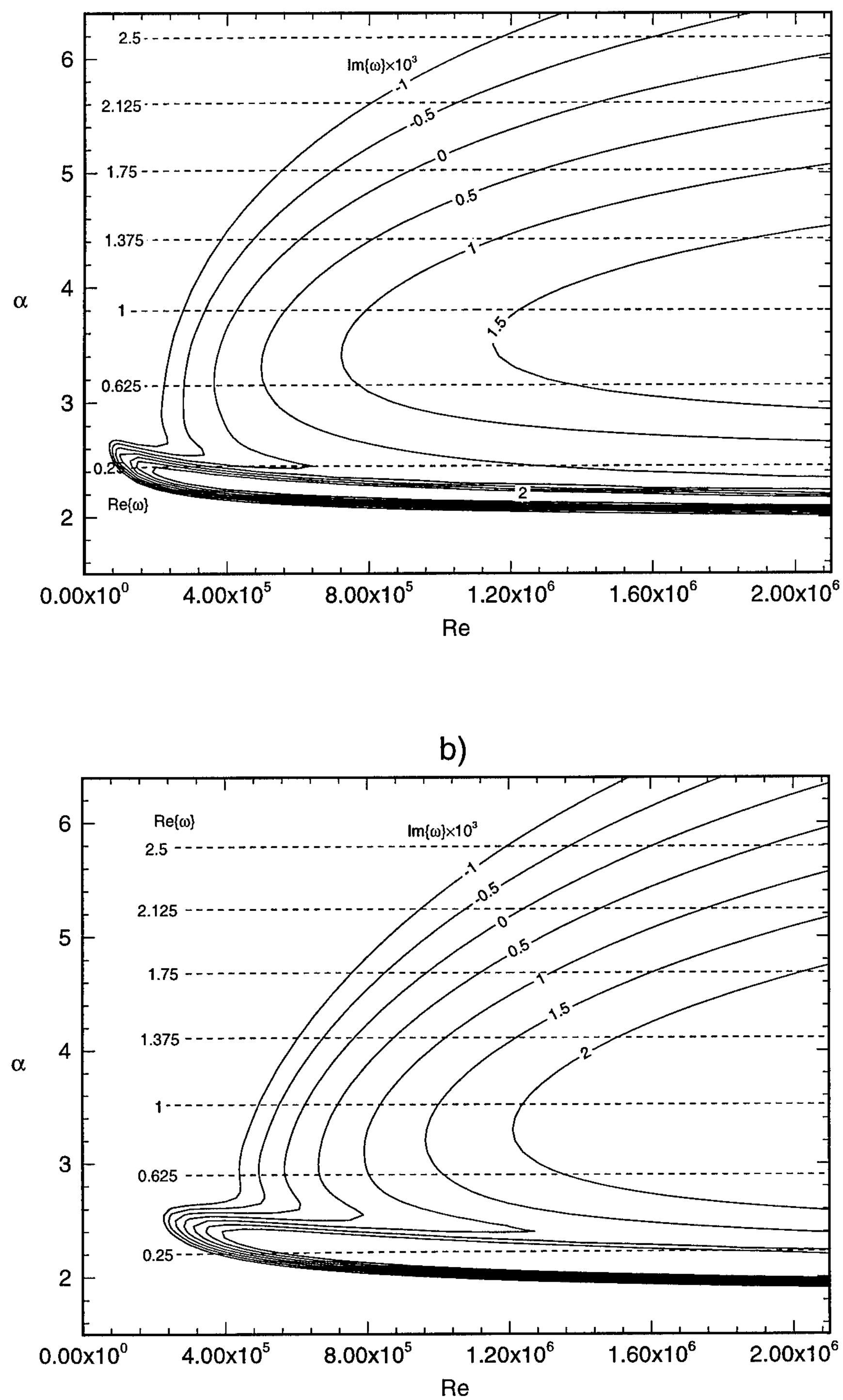


Figure 7: Instantaneous contours of the perturbations of the velocity vectors for the DNS of the receptivity to a weak freestream acoustic waves by a hypersonic boundary layer over a parabola ($M_\infty = 15$ and $Re_\infty = 6026.55$).

a)



b)

Figure 8: The second mode growth rate contours for hypersonic plane Couette flow as a function of wave number α and Reynolds number: a) $M_\infty = 5.0$, b) $M_\infty = 10.0$.

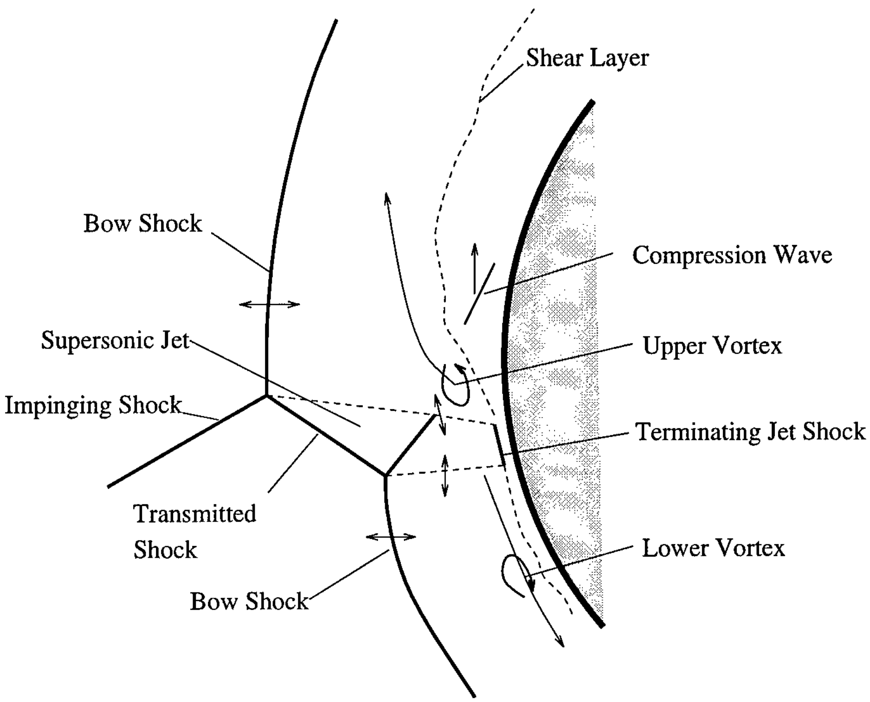


Figure 9: Schematic of the vortex shedding mechanism responsible for the unsteadiness of type IV shock-shock interference heating flow. The vortices are shed out of phase with respect to each other. The arrows indicate the motions of the flow structures.

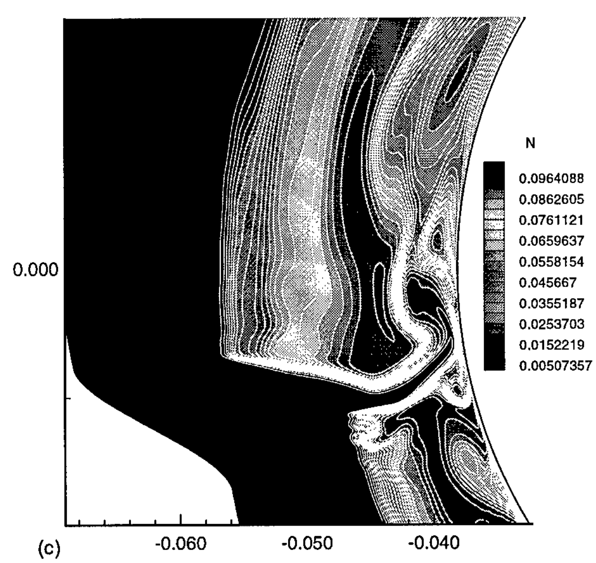


Figure 10: Instantaneous contours of N mass fractions for unsteady type IV shock-shock interference heating flow solutions obtained by the unsteady Navier-Stokes equations with a nonequilibrium real-gas model. Flow conditions: $M_\infty = 8.03$, $T_\infty = 800K$, $T_{wall} = 1000K$, and $P_\infty = 985pa$. Note the alternating regions of high and low N concentration that are shed along the upper surface.